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13. ABSTRACT (Maximum 200 words)

An experimental and theoretical investigation of convection at high Rayleigh numbers was carried out with the goal of trying to understand the role that convection plays in oceanic mixing processes. Numerical models were constructed that solved the two-dimensional Navier-Stokes and heat conduction equations under the same conditions as those for experiments on constant heat-flux convection and for the cabbeling instability. For constant heat flux it was found that at high Rayleigh numbers there were two length scales, the thickness of the thermal boundary layer and the total depth of the fluid layer. This seems to be consistent with the thermal patterns, which had a length scale approximately the mixed layer depth, at the ocean surface found using an infrared scanner from an airplane. The cabbeling simulations seem to be fairly accurate representations of the laboratory experiments. The comparison of the cabbeling instability to oceanic phenomena is continuing, but preliminary results seem to indicate that it may be important in the Antarctic.

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Goals:

The ultimate goal of this research was to understand the role that convection plays in water mass formation and modification.

Objective:

The immediate objective was to study convection at high Rayleigh numbers with particular reference to transfer of energy between different time and space scales. In this way we hoped to understand how convection in deep layers of fluid, such as the oceanic mixed layer, develops in time and transfers heat and salt.

Approach:

In this investigation we combined laboratory experiments with numerical simulations at the same or similar conditions in order to study the physics of high Rayleigh number convection and to relate these convective phenomena with those found in the ocean.

Tasks completed:

We developed three numerical models: (1) convection between two parallel plates maintained at constant temperature, (2) convection induced by constant heat flux from a single plate, and (3) convection induced by the cabbeling instability (due to a nonlinear equation of state). These models were implemented on and run on a variety of "super computers", including the IBM 9091, Cray-2, X-MP and Y-MP computers. We constructed a 1.2 meter tank with a control system for monitoring and controlling the heat flux at the bottom so that experiments on one-sided convection could be carried out. We completed a series of experiments using a traversing probe to

investigate the horizontal wavenumber spectra of the temperature field in developing convection in the 1.2 meter tank. We also completed numerical simulations at the same Rayleigh numbers as used in the experiments. In addition we carried out a series of experiments on the effect of boundary conditions on the stability of the flow patterns as part of an investigation into the possibility that three-dimensional instabilities are responsible for part of the energy exchange between different length and time scales. We also started to relate the results from this investigation with time series of temperature and salinity profiles from a region of active subsurface convection in the Weddell Sea. We attended the International Symposium on the Oceanography of the Indian Ocean 14 - 16 January 1991 at Goa, India, and presented a paper on bottom water formation in the southeastern Indian Ocean. We also made some very useful contacts with Indian oceanographers and hope that we may collaborate with them in the future. We have continued to make plans for participation in the Indian Ocean ARI. Finally, we completed the analysis of data taken from the upper ocean during MIZEX-84 and published these results (Eckert and Foster, 1990).

#### Scientific results:

On the theoretical side we have constructed two numerical models for high Rayleigh number convection. These models both solve the complete two-dimensional, nonlinear Navier-Stokes and heat conduction equations simultaneously using the pseudospectral method. For the conventional convection arrangement, in which the fluid is confined between two parallel plates maintained at constant temperature, we have investigated the behavior of the system at Rayleigh numbers up to  $3 \times 10^6$ . Most of these calculations have been at a Prandtl number of 10 (water at 10C). For Rayleigh numbers above 40,000 the flow becomes oscillatory. The frequency of oscillation increases with Rayleigh number, but above about 100,000 the flow becomes "chaotic" (Foster, 1988). The second model simulates the conditions of our laboratory experiments, as well as those of the sea surface, and uses a single constant heat-flux surface with the other surfaces insulated. This system has been investigated at flux Rayleigh numbers up to  $8 \times 10^9$ . In the horizontal wavenumber investigation we found that there was good agreement in the basic phenomena observed in both experimental and numerical simulations. This was quite surprising since the velocity boundary conditions were not the same, and the simulations were two-dimensional. Evidently, in our configuration the thermal boundary conditions determine the basic flow while the velocity boundary conditions are of secondary importance (Foster, 1989). The primary conclusion that we can draw at this time is that there are two spatial and temporal scales involved in high Rayleigh number convection. These scales are related to the thickness of the thermal boundary layer and the depth of the layer of fluid. In the case of the ocean these layers would be a few centimeters thick for the thermal boundary layer and a few tens of meters for the fluid layer -- the mixed layer depth (Foster, 1991a). Two-dimensional simulations also indicated that the thermal boundary condition at the heated surface would be very important in determining the stability of the flow pattern and an

insulating boundary condition would be much more unstable than a conducting boundary. Flow visualization experiments using a time-lapse video system showed that qualitatively the flow pattern for an insulating boundary was indeed less steady than for a conducting boundary. Quantitative results were obtained by digitizing the signal from a thermistor probe in the tank and calculating power and variance spectra. The spectra did not show a great difference between the two boundary conditions until the Rayleigh number was above about  $4 \times 10^{**7}$  at which point the insulating boundary showed more energy at longer periods than for the conducting boundary. The visual observations are apparently much more sensitive indicators to long-term stability than are power spectra (Foster and Buchter, 1990). With support from NSF we have obtained several very interesting time series of CTD profiles from the central Weddell Sea. These profiles show the time development of a series of large (10's to 100's of meters deep) step-like structures that are apparently due to the cabbeling instability although the pressure instability generated by the changes in pressure induced by internal waves probably also plays a role (Foster, 1991b, 1992). Our convection work has been very useful in understanding this oceanic phenomenon.

#### Accomplishments:

The most important finding from this investigation was the determination that two length scales, the thermal boundary layer thickness and the total depth of the fluid layer, are involved in high Rayleigh number convection.

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